

REPORT No. 58

CHARACTERISTICS OF HIGH-TENSION MAGNETOS



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CHARACTERISTICS OF HIGH-TENSION MAGNETOS

Part I.—CYCLE OF OPERATION OF JUMP-SPARK IGNITION SYSTEMS

Part II.—TRANSFORMATION RATIO AND COUPLING IN HIGH-TENSION MAGNETOS

BY

F. B. SILSBEE

REPORT No. 58.

PART I.

CYCLE OF OPERATION OF JUMP-SPARK IGNITION SYSTEMS.¹

By F. B. SILSBEE.

RÉSUMÉ.

The purpose of this report is to outline briefly the succession of operations which occur in high-tension ignition systems in order to show the connection between the various phenomena concerned and their relative importance on a basis of the energy transformed. It is hoped in later reports to give in detail the results of measurements of various individual parts of this cycle of operations, and the present report is issued as a basis for interrelating these later discussions.

Throughout the report numerical values are given for the different electrical quantities involved. These values have been obtained by actual measurements of various magnetos recently tested at the Bureau of Standards. They may be considered as typical of this class of apparatus. Figures 4 to 17, inclusive, give reproductions of oscillograms taken on magnetos while operating under various conditions.

The cycle of operation of the jump-spark system can be split up into a number of periods. During each period the electrical phenomena proceed under fairly definite conditions, each period in turn being separated from the one preceding and the one following it by an abrupt change of conditions.

Period No. 1 includes the building up of current in the primary winding as a result of either the impressed voltage from a battery or the voltage generated by the rotation of a magneto armature. The result of this period is the establishment of a current (I_b) in the inductive winding.

Period No. 2 covers the short interval between the instant of the interruption of the primary current by the circuit breaker and the breaking down of the spark gap in the engine cylinder. During this period the magnetic energy of the coil is in part transformed into electrostatic energy and charges the condenser and capacity of the secondary leads.

Period No. 3 is a second very short interval (0.00005 second) beginning at the instant at which the spark gap breaks down and lasting until a steady arc is established in the gap.

Period No. 4 extends from the establishment of the secondary current in a steady arc across the spark gap to the extinction of the spark. Its duration is quite appreciable and may be several thousandths of a second. It is during this period that most of the spark energy is dissipated.

Period No. 5 covers the short interval during which the spark is being extinguished by the closing of the contact breaker.

Period No. 6 covers the remainder of the cycle during which the circuits are practically free from current previous to the beginning of period No. 1 of the following cycle.

The above division into periods applies with slight modifications to both battery and magneto ignition systems. It is believed that a clear recognition of the very different conditions which exist during the various periods will result in a better comprehension of the extremely complicated phenomena which occur in these forms of electrical apparatus.

¹ This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 20.

INTRODUCTION.

The purpose of this report is to outline briefly the salient features of operation of the high-tension magneto, and of the similar battery ignition systems, and to trace the various transformations of energy which take place. The results of numerous measurements on such systems as have been studied at the Bureau of Standards will be quoted in illustration of these properties. These phenomena are doubtless understood by magneto designers, but with the exception of the excellent papers by Armagnat and Young referred to below, the literature of the subject is very meager and consists chiefly in elementary expositions for the instruction of the amateur automobilist.

The cycle of operations of a jump-spark system can be divided into a number of periods. During each period the electrical phenomena proceed under fairly definite and constant conditions, each period being separated from the one preceding and the one following it by an abrupt change of conditions. It is hoped in later reports to discuss in greater detail and in a more quantitative manner the phenomena of certain of the periods; and the present report is issued as a basis for interrelating these later discussions.

The operation of the usual forms of battery ignition systems is quite similar in many respects to that of the magneto, and the greater part of the following discussion is applicable to both, with suitable changes in the values of the various constants. The principal points of difference in the two types of apparatus are discussed later under "Battery Systems."

Throughout this report frequent reference will be made to numerical values of the various quantities which may be expected in a typical case. For this purpose a magneto having the constants in the following Table I has been chosen. These constants do not precisely fit any individual magneto but are representative of values measured on a number of different types recently tested.

TABLE I.—Constants of Typical Magneto.

Primary turns (N_1).....	160.
Secondary turns (N_2).....	8,000.
Ratio of turns (n).....	50 : 1.
Primary resistance (R_1).....	0.5 ohm.
Secondary resistance (R_2).....	2,500 ohms.
Primary inductance (L_1).....	0.015 henry.
Mutual inductance (M).....	0.74 henry.
Secondary inductance (L_2).....	36 henrys.
Primary condenser (C_1).....	0.2 microfarad.
Secondary (distrib.) capacity (C_2).....	50 micro-microfarads.
Normal speed of operation.....	2,000 r. p. m.
Primary current at break (I_b).....	4 amperes.
Maximum current in spark.....	0.075 ampere.
Breakdown voltage of gap.....	5,000 volts.
Sustaining voltage of gap.....	600 volts.

OUTLINE OF OPERATION.

The high tension magneto combines in a single machine the functions of an electric generator and of an induction coil, and these two functions are to a considerable extent independent of one another.

The circuits of a high-tension magneto are substantially as shown in figure 1, P being the primary winding which has a few turns of coarse wire and consequently a low resistance, while the secondary winding S has several thousand turns of fine wire. The two coils are wound one over the other on a common iron core, which (in the ordinary or shuttle type) has the form shown in figure 3. Condenser C_1 is connected across the terminals of P primarily to reduce the sparking at the contact breaker B . The electrostatic capacity between the secondary winding or high tension leads and the grounded frame of the machine is sufficiently large to have a material effect on the operation. This capacity is in part distributed along the windings and various portions are consequently subject to different voltages. The effect of this capacity may, however, be approximately represented by an equivalent condenser connected as shown dotted in C_2 , figure 1,

The rotation of the armature in the field of the permanent magnets NS , figure 3, generates a current in P which flows through contacts B . When a spark is desired, breaker B is suddenly opened by a cam. The current decreases rapidly, producing a high voltage $M \frac{dI}{dt}$ in the secondary. This is led through a distributor (not shown) to the spark gap G in the proper cylinder of the engine. This gap breaks down at usually much less than the maximum available voltage and the magnetic energy originally stored in the primary is transferred to the secondary and dissipated in the gap.

Magnetos may be classified as "two-spark," "four-spark," etc., according to the number of sparks produced per revolution of the rotor. The shuttle core type gives two sparks while most inductor type machines give four. As a rule all the alternations are substantially alike except for the polarity of the induced voltage, though lack of symmetry in a four-spark machine may cause slight differences. Special magnetos designed to fire V-type motors such as the "Liberty 12," where the angle between the blocks is not a simple submultiple of the angle between the cranks, may have successive alternations of materially different wave form. (See figure 4, which shows the primary and secondary currents of such a magneto.) The discussion below, however, will apply to any one alternation in any case.

DETAILS OF OPERATING PERIODS.

The time occupied by one alternation of the magneto may be subdivided into six periods during each of which the circuit conditions are substantially constant, but between which there is a more or less abrupt change in these conditions. These periods are listed in the following table and discussed in more detail below. (See figure 12.)

Period.	Begins.	Ends.	Conditions during period.
1	Max. flux.....	Breaker opens.....	Breaker closed, current building.
2	Breaker opens.....	Gap breaks down.....	Breaker open, gap open, capacity charging.
3	Gap breaks down.....	Steady arc established.....	Breaker open, gap closed, capacity discharging.
4	Arc established.....	Breaker closes (arc dies out).....	Breaker open, gap closed, coil discharging.
5	Breaker closes.....	Capacity fully discharged.....	Breaker closed, gap open, capacity discharging.
6	Capacity discharged.....	Max. flux.....	Breaker closed, gap open, eddy currents dying out.

PERIOD 1.

During Period 1, the breaker is closed and the armature rotates from the position of maximum flux to the firing position where the cam causes the breaker to open. This period corresponds to about 100° rotation in our typical example and hence lasts 0.008 seconds. During this time the reduction in flux builds up a current (in our example 4 amperes) which tends to maintain the original flux after the rotor has passed the neutral position.

If there were absolutely no resistance in the primary winding or breaker contacts the current would build up to such a value that the armature flux would be maintained constant when rotated to a position at right angles to or even opposing the magnetomotive force of the permanent magnets. This maintenance of the flux is shown quite clearly in figure 20, which shows the total flux through the armature core plotted against angular position (or time) for three different conditions. Here curve I shows the flux through the core on open circuit and is due to the permanent magnets only; curves II and III give the total flux during normal operation of the magneto at low and high speed respectively, and curve IV shows the flux if the primary is left short circuited throughout a complete cycle. The action of the primary circuit in thus closing about the flux produced by the permanent magnets and permitting it to be moved unaltered to a new position is in a sense analogous to the action of an electrophorous in which the charge produced by induction from the exciting charge on the dielectric slab is insulated and moved out of the field of the permanent charge. In either case, the energy is obtained from the motion of the system and the permanent magnets or fixed charge suffer no depletion. The closing of the breaker corresponds to the opening of the ground connection to the electrophorous plate at the beginning of its motion, and the opening of the breaker corresponds to the discharge of the plate after its removal from the slab.

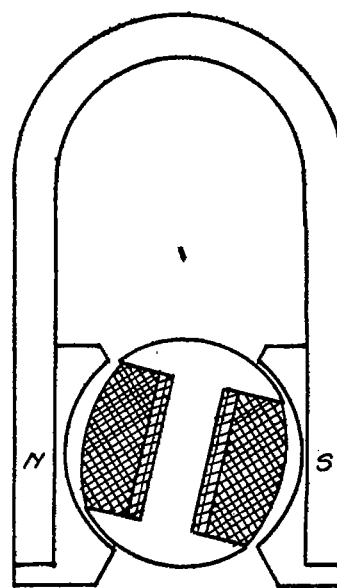
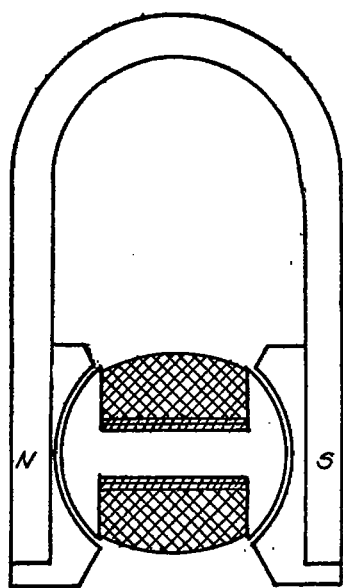
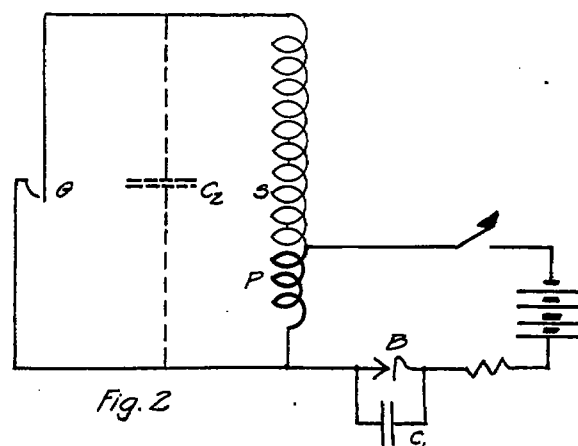
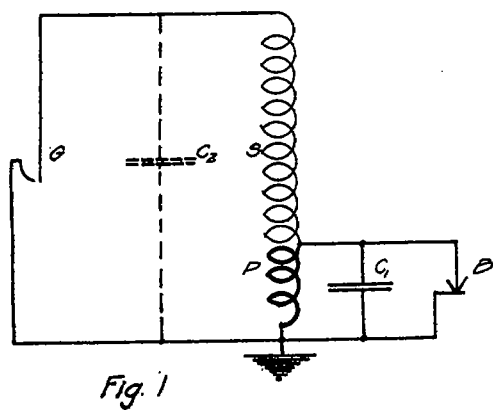
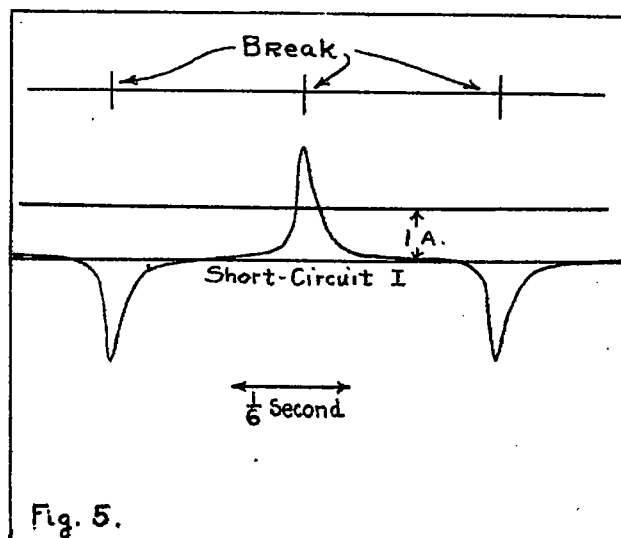
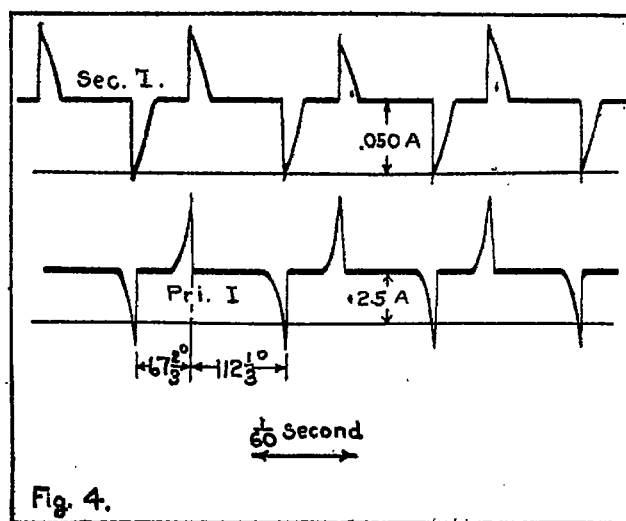
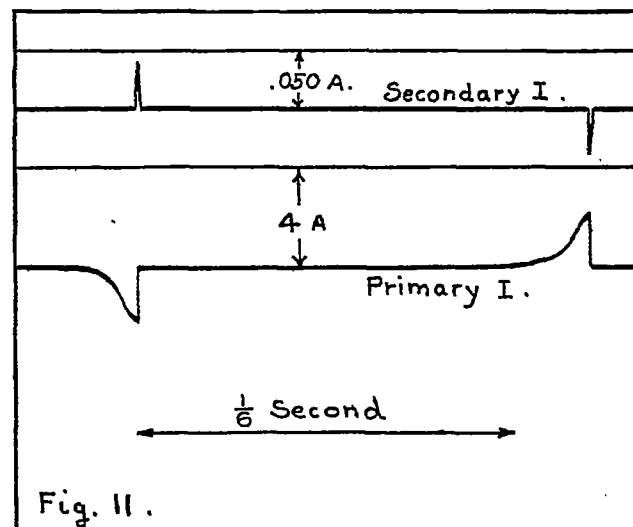
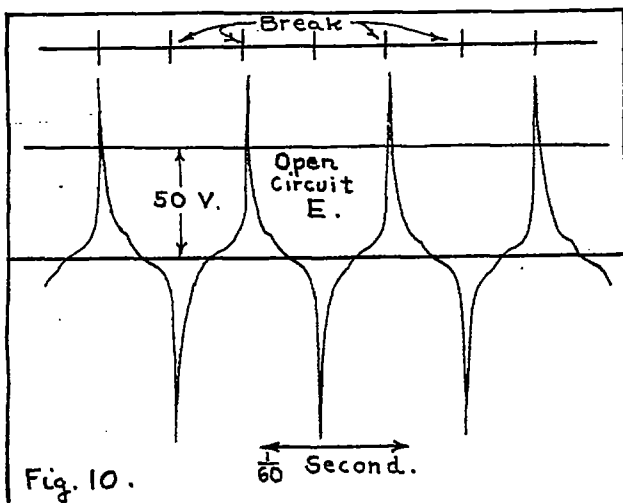
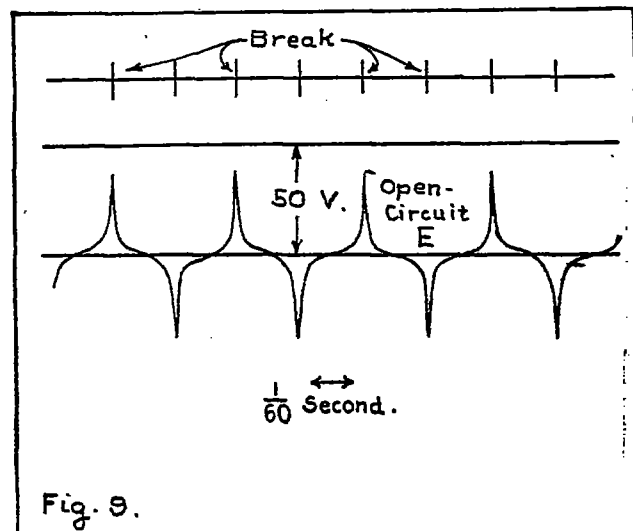
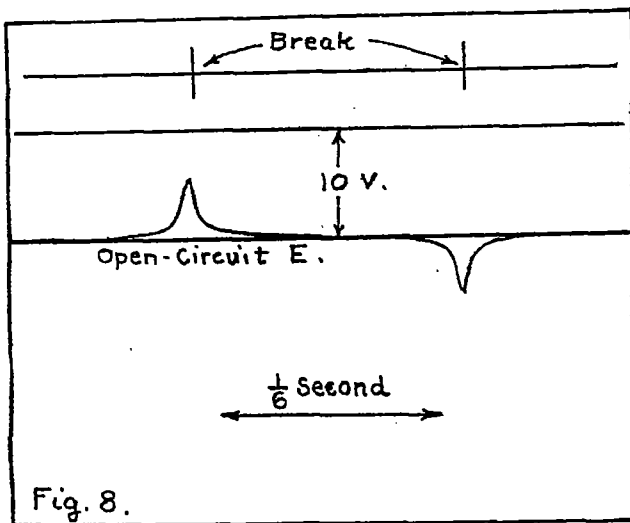
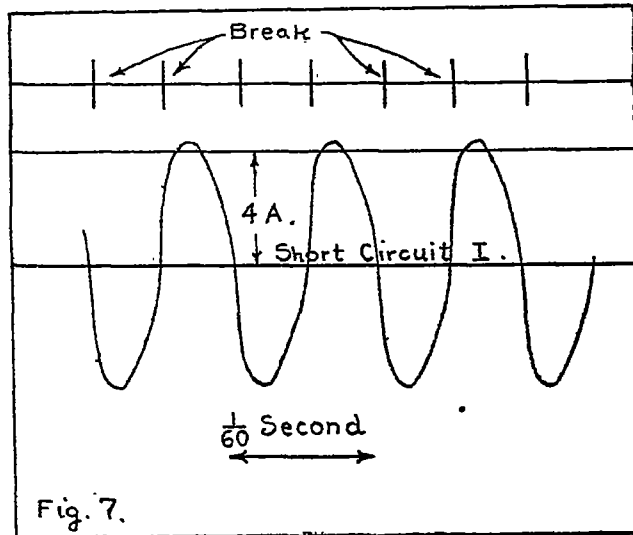
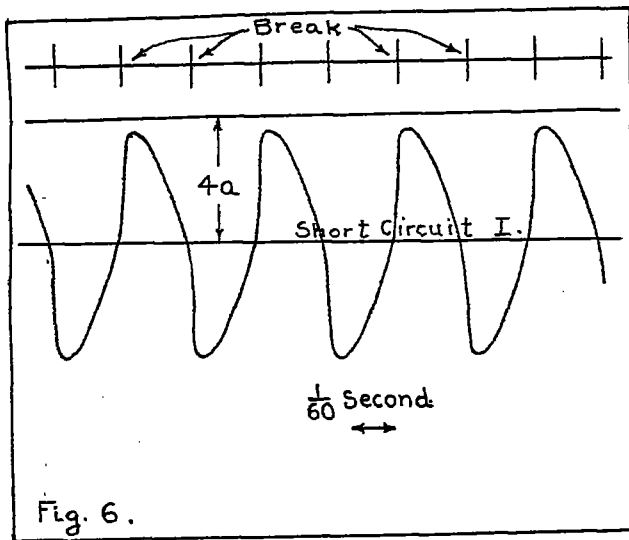


Fig. 3





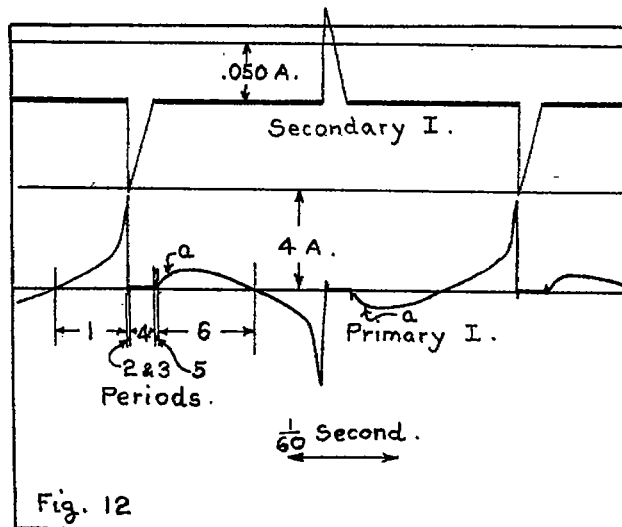


Fig. 12.

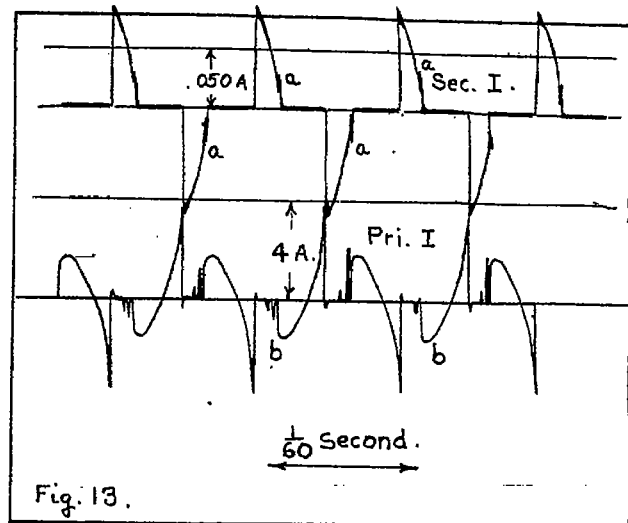


Fig. 13.

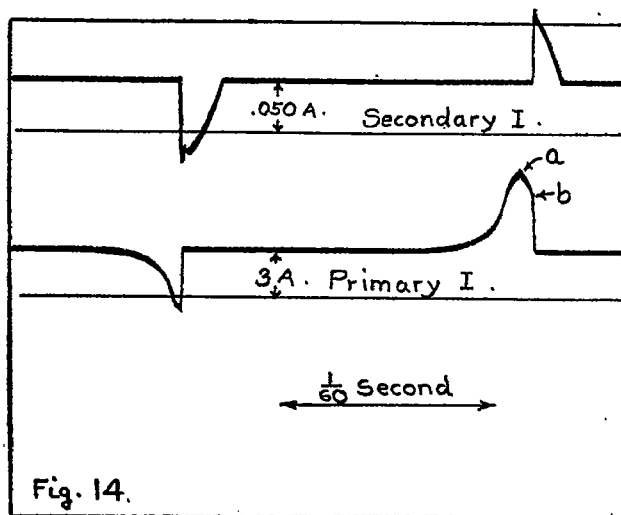


Fig. 14.

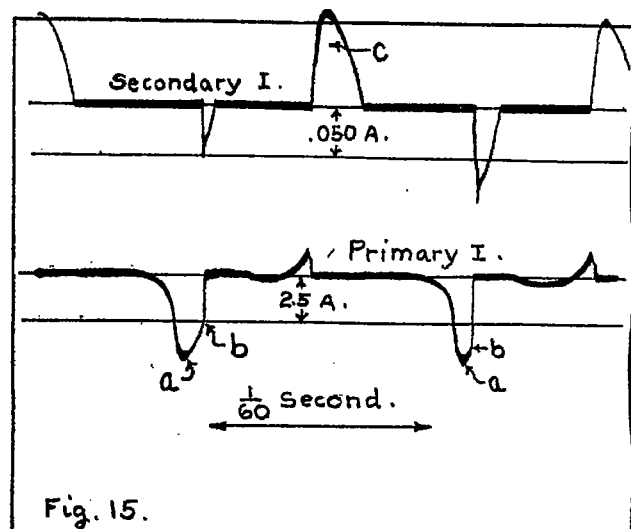


Fig. 15.

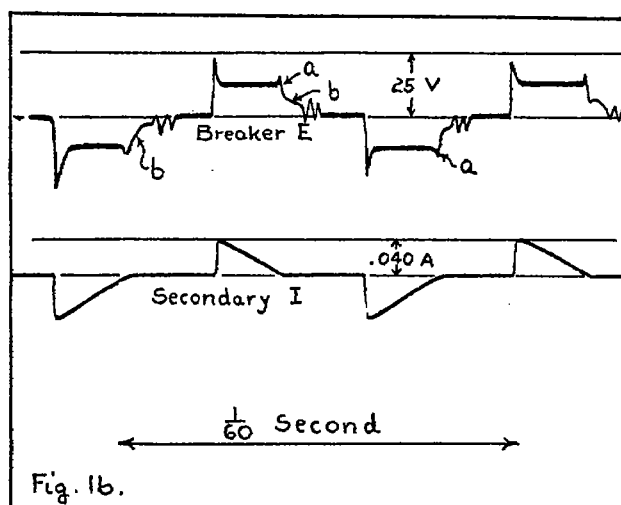


Fig. 16.

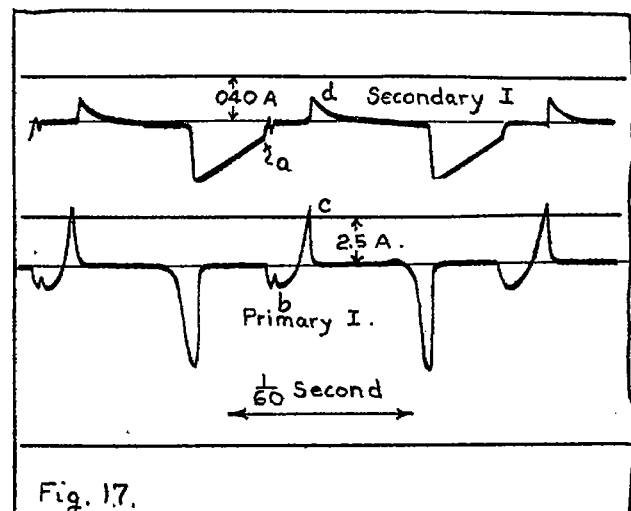


Fig. 17.

In the actual magneto the primary resistance materially reduces the generated current and the actual flux at break is (as shown in plot 20) considerably less than the maximum open circuit flux.

It should be noted that there is a very considerable difference in the operation of a magneto at low and at high speeds. In the former case, the primary current is limited chiefly by the resistance of the windings and has approximately the same wave form as the generated voltage. The maximum current reached is proportional to the speed and is small so that the total energy stored magnetically is also small. Consequently at "break" nearly all of this energy must be transferred to the electrostatic capacity of the windings and condenser before the voltage is sufficiently high to jump a normal spark plug gap. At high speeds on the other hand the current is limited by the inductance of the circuit and is nearly independent of speed. The current and magnetic energy are very much greater and only a negligible part of this energy is expended at "break" in charging the capacities to the breakdown voltage. This effect is shown in plot 21 in which the current generated in the short-circuited primary at various speeds is plotted against speed. The lower curve shows the effective (root-mean-square) value as observed with a hot wire ammeter, and the upper curve the maximum value of the current wave from oscillograms. It is evident that above 400 revolutions per minute the current is large and independent of the speed while at low speeds the current is smaller and of more peaked wave form. This is also shown by a comparison of figures 5 and 6 which show the difference in the wave form of the primary current on short circuit at low and high speeds.

The primary current finally attained at break, I_b , is of the greatest importance in determining the performance of the apparatus. It can be determined directly by an oscillograph by inserting a shunt of about 0.025 ohm in series with the primary and connecting the oscillograph vibrator across this shunt. This method has the disadvantage of introducing resistance into the circuit and thereby disturbing conditions. At high speeds this disturbance is entirely negligible, for the current is then limited by the inductance rather than the resistance of the circuit. At low speeds, however, the resistance predominates and the error might amount to 5 per cent or 10 per cent at very low speeds. The current waves in figures 4 to 19 were obtained in this manner.

Other methods for determining the primary current wave are based on first obtaining the open-circuit voltage wave or the flux wave and then computing the current by a step-by-step process.

Armagnat¹ and Young² have developed the following equations for this purpose from the fundamental equation

$$e = Ri + L \frac{di}{dt} \quad (1)$$

which applies to any inductive circuit. By integrating this over a short interval $\Delta t = t_2 - t_1$ they obtain

$$\int_{t_1}^{t_2} e dt = R \int_{t_1}^{t_2} i dt + L(i_2 - i_1) \quad (2)$$

Letting $A = \int_{t_1}^{t_2} e dt = \text{area under the voltage-time wave between } t_2 \text{ and } t_1$, and assuming that i can be taken as changing linearly over the short time interval considered we get

$$A = R \Delta t \frac{i_2 + i_1}{2} + L(i_2 - i_1) \quad (3)$$

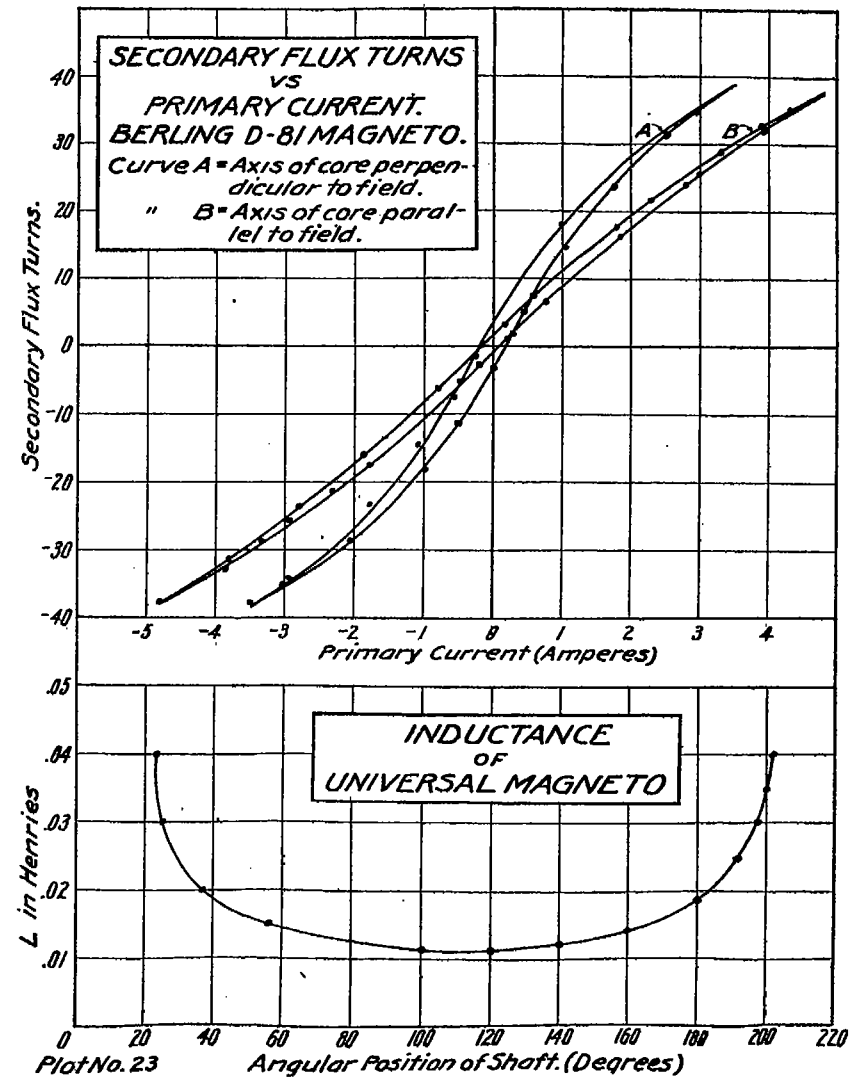
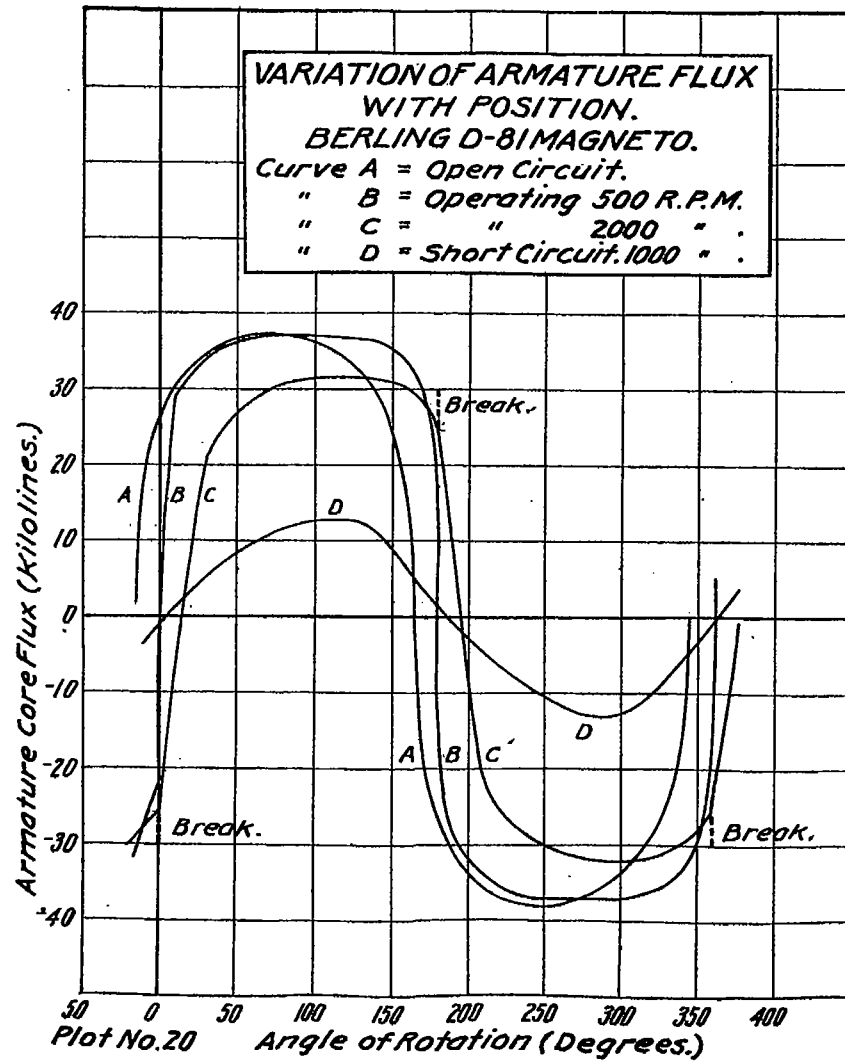
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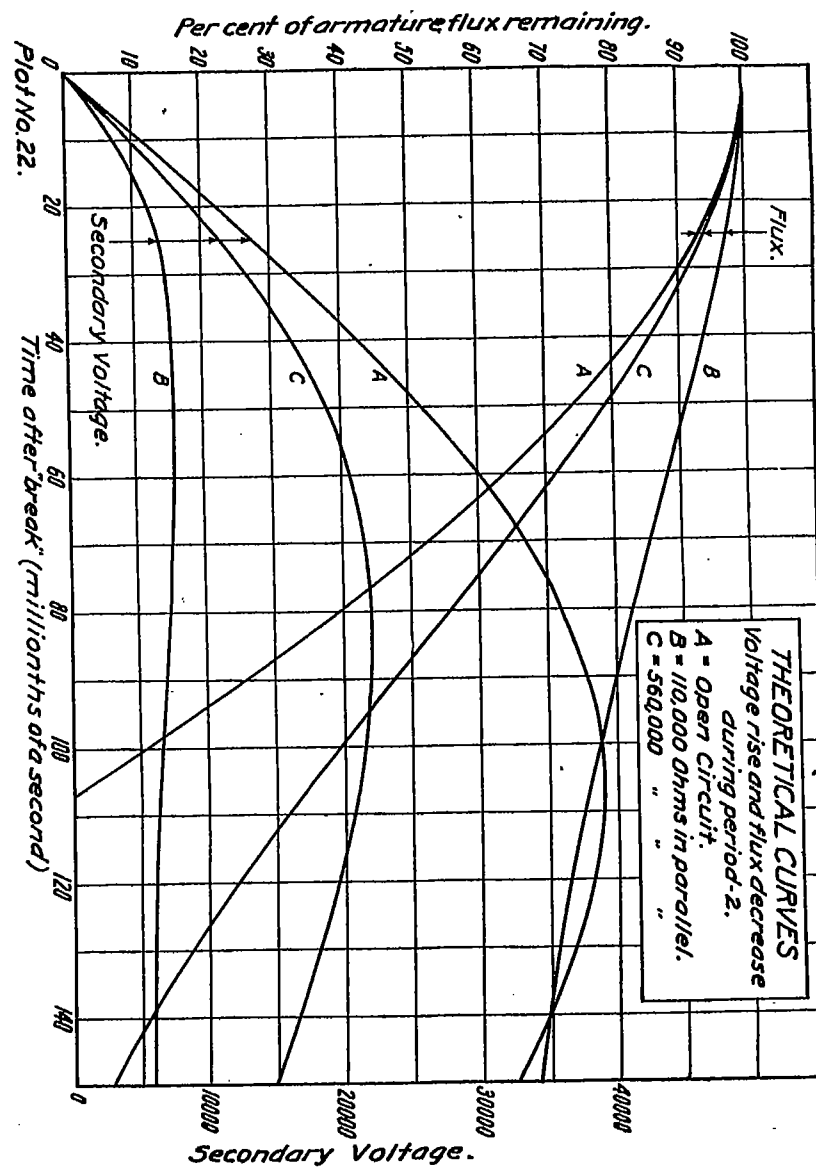
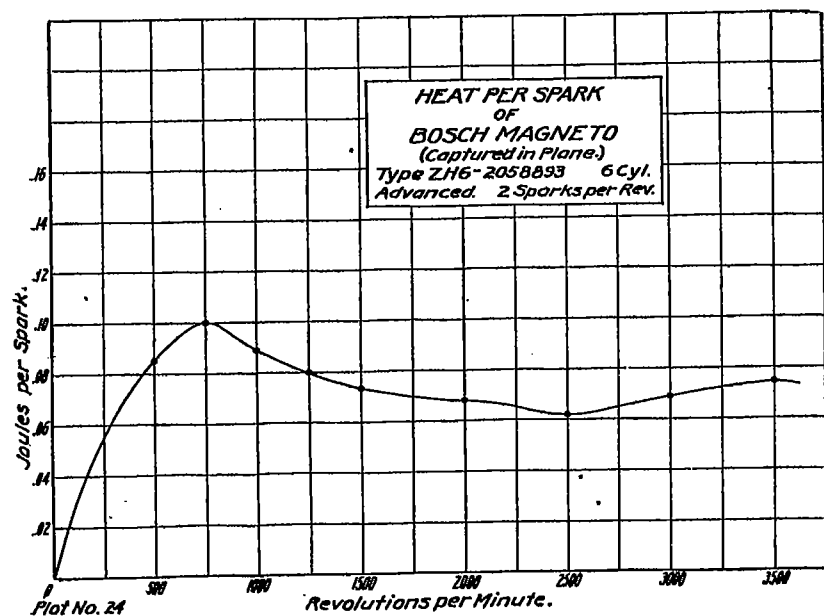
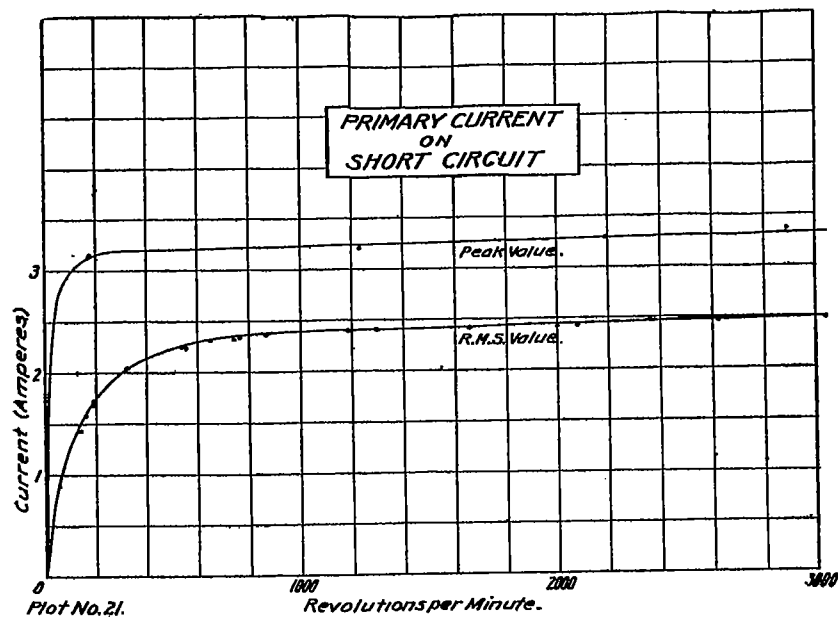
$$i_2 = \frac{2A + i_1(2L - R\Delta t)}{2L + R\Delta t} \quad (4)$$

This gives the working equation for the current i_2 when the current at the preceding time i_1 is known.

¹ Armagnat, H. Rev. Electricité 23, p. 321-333, 1915. Electrician 76, p. 365-399, 1916.

² Young, A. P. Aeronautical Jour., pp. 142-252, 1917. Automobile Engineer, March, 1915.





Since e in the above equation is the E. M. F. generated by the flux from the permanent magnets only, we may write

$$e = \frac{-N d\phi_m}{dt} \quad (5)$$

and

$$A = N (\phi_{t_1} - \phi_{t_2}) \quad (6)$$

and hence may compute i from the open-circuit flux wave by equation (4).

The voltage wave (figures 8, 9, and 10) may be observed directly with the oscillograph by connecting the vibrator in series with a resistance of several hundred ohms across the breaker points (the latter being permanently insulated). This connection does not appreciably interfere with the conditions of operation. An alternative method is to observe the primary flux wave with the ballistic galvanometer and obtain the voltage wave from this by the equation

$$E = -N \frac{d\phi}{dt} = -N \omega \frac{d\phi}{d\alpha}$$

PERIOD 2.

Period 2 is of extremely short duration (about 0.00002 second) and extends from the instant of opening of the breaker to the time of breakdown of the spark gap.

During this period both the breaker and spark gap are open, and the system consists of two inductance coils very closely coupled magnetically and each shunted by capacity. Since it is impossible without the expenditure of infinite power to abruptly change the current in an inductive circuit, the primary current now flows into the condenser rapidly charging it. The charge in the condenser offers a continually increasing electromotive force in opposition to the primary current, which therefore decreases at a constantly increasing rate. The decrease of flux resulting from this decrease of primary current generates an E. M. F. in the secondary winding which in turn sends a charging current into the distributed capacity of the secondary winding and leads. The net effect is, therefore, a partial transfer of current from the primary to the secondary windings. If the spark gap were not present this process would continue until the magnetic energy had been entirely converted into electrostatic energy in the charge capacities, at which time the currents would have been brought to zero and the flux would have the value determined by the permanent magnets alone. The maximum voltage which would be reached at this time, if energy losses are neglected, is given approximately by the equation,

$$E = I_p \sqrt{\frac{L}{C}}$$

where L is the inductance of the primary winding and C the capacity which is equivalent to the combined effect of both the primary condenser and secondary distributed capacity. For our typical example this would reach 70,000 volts. Actually there is throughout this time a steady drain of energy due to the resistance of the windings, the dielectric loss in the condenser, and especially the eddy currents in the iron core and pole pieces. These losses are sufficient to reduce the maximum voltage to about 40,000 volts.

The curves in plot 22 show the rise of voltage and decrease of flux as computed for our typical example after making certain simplifying assumptions.

If account is taken of the magnetic leakage flux between the two coils, the voltage wave will be found to be a combination of that shown with a second oscillation of higher frequency and smaller amplitude. The theory of this effect has been worked out by Prof. E. Taylor Jones (Phil. Mag., August, 1918).

The curves marked "open circuit" are computed for the case when there is no energy loss except that in the resistance of the windings. The second pair of curves computed for a shunt of 560,000 ohms connected across the high tension terminals correspond to a drain of energy

approximately equal to that to be expected from eddy currents. The third pair of curves correspond to a shunting resistance of 110,000 ohms, which might occur with a partially fouled spark plug. The assumption upon which all these curves have been constructed is that the spark gap does not break down. In normal operation, however, the spark gap breaks down at about 6,000 volts, and consequently new circuit conditions are introduced before the resultant flux has decreased materially from its value at break.

In the above discussion it is assumed that the breaker succeeds in opening the circuit without sparking at the contacts. If an arc occurs at break, some of the energy is dissipated then, and the rate of decrease of primary current, and consequently the induced secondary voltage, is much less. Figures 14 and 15 show the excessive arcing at the breaker which occurred when a special cam was used giving a very slow rate of separation of the breaker points. The contacts separate at *a*, but the arc maintains the current until *b*, when it finally breaks and a considerably reduced spark results.

PERIOD 3.

When the gap has broken down it affords a conducting path, and the charged secondary capacity and leads immediately discharge through it. The exact conditions existing in the spark, particularly immediately after break down, are still obscure, and it is possible that this first discharge may be oscillatory and of high frequency.

Tests made by loosely coupling a sensitive wave meter to the secondary circuit of a magneto have shown no indication of resonance with any oscillations within the range between 30,000 and 1,000,000 cycles, although the apparatus used was sufficiently sensitive to have detected a steady oscillation of 0.2 milliampere throughout the range. A circuit formed by connecting a loop from one point of the distributor to ground was found to absorb oscillations of frequencies from 3,000,000 to 10,000,000 cycles per second for various configurations of the loop, but no such absorption was detected at frequencies from 2,000 to 30,000 cycles per second. Any oscillations which may have been present must therefore have been very feeble or very highly damped.

In addition to this discharge of the leads, the current increases rapidly in the secondary, since it is now practically short-circuited by the gap; and the primary current simultaneously decreases at such a rate that the total ampere turns linking the main flux are maintained with little loss. The charged primary condenser hastens the decrease of primary current and ultimately reverses it for a short time while the condenser energy is being shifted to the secondary side. The dissipation of energy in the gap, however, is probably sufficient to damp out any oscillations from this condenser.

The net results of the three simultaneous processes during this period are, therefore, (a) the discharge into the gap of the energy stored in the capacity of the leads; (b) the complete stopping of the primary current and the formation of a secondary current giving approximately the same ampere turns; and (c) the dissipation in the windings and gap of the energy in the primary condenser. The duration of the period is of the order of one cycle of an oscillation, determined by the primary condenser and the leakage inductance of the windings (approximately 0.00005 second). The energy discharged into the gap during this time is about 0.002 joules, which recent measurements indicate is just about sufficient to ignite an explosive mixture. It is therefore probable that this period 3 is the one fundamental to ignition.

PERIOD 4.

Period 4 extends from the establishment of the secondary current in a steady arc across the spark gap to the extinction of the spark. During this time there exists across the gap a steady discharge which lasts for a considerable time (0.003 second in the case of a 5-mm. spark gap in air). It has been found experimentally that the voltage drop in the gap is roughly constant during this entire period, as is shown by oscillograms such as figure 16. The capacities therefore remain with a small charge and have little effect on the phenomena. The energy dissipated in the gap is supplied by the decay of the secondary current in the coil, and since the voltage is approximately constant and

$$E = -L \frac{di}{dt}$$

the current drops off linearly with time. The instantaneous resistance of the spark ($R = \frac{E}{I}$) is thus seen to increase rapidly from about 8,000 ohms at the beginning of period 4 to a very high value at the end. It is during this period that the major part of the energy of the spark is liberated in the gap.

In the case of the induction coil of a battery system the magnetic field is the only source of energy and the heat dissipated in the gap may be computed with a fair degree of accuracy from the stored energy $\frac{1}{2} L I_s^2$ by correcting for the $I^2 R$ loss in the secondary winding. In a magneto, however, particularly when operating at full advance, the voltage generated by the rotation of the secondary winding in the magnetic field is comparable with the sustaining voltage across the gap; and a very considerable amount of energy is thus forced into the secondary by the rotation of the armature. This may cause a very marked "hump" in the secondary current wave, such as appears at *c* in figure 15. The E. M. F.'s in the circuit satisfy the equation:

$$E_r - L_2 \frac{di_2}{dt} = E_s + R_2 i_2$$

where E_r is the voltage generated by the rotation of the armature in the magnetic field and E_s is the voltage drop required to sustain the arc between the gap terminals. The corresponding energy equation may be written:

Energy derived from rotation + energy released by breaking primary = heat in spark + loss in secondary copper.

The following table gives typical values of these quantities computed from oscillograms together with the spark heats observed with a calorimeter in three particular cases:

	Magneto.		Battery and coil.
	Advanced.	Retarded.	
Magnetic energy.....	0.05	0.15	0.019
Rotational energy.....	.19	.00	.00
Total.....	.24	.15	.019
Heat in spark (calorimeter).....	.15	.08	.018
Heat in spark oscillograph.....	.15	.11	.014
Secondary copper loss.....	.04	.03	.001
Stray losses (by difference).....	.05	.01	.004
Total.....	.24	.15	.010

In the case of iron-clad circuits such as are here considered the term "inductance" is somewhat vague and is difficult to define precisely. It evidently varies with the angular position of the rotor, with the current flowing, and (because of eddy currents) with the rate of change of current. It is possible, however, with the armature clamped in any given position, to determine by the ballistic galvanometer the change in flux turns corresponding to any given change in current, and the equivalent inductance can then be computed. Plot 23 shows hysteresis loops determined in this way. This illustrates the relation between the secondary flux turns and the primary current for a shuttle-type magneto when the armature is clamped in the positions of zero flux and maximum flux, respectively. In the first position, the permanent magnets send no flux through the armature core, and the loop was obtained in the usual manner with currents in both directions. In the second position the magnets alone would produce the flux indicated by the apex of the loop. The curve was obtained by applying currents opposing the magnets and noting the corresponding changes in flux. From curves of this kind it is possible to establish approximately the equivalent inductance corresponding to any given conditions.

A much simpler method is to measure the effective inductance of the windings while clamped in any position with alternating current, using either a bridge or a voltmeter-ammeter-wattmeter method. A typical curve obtained in this way is shown in plot 24. This method was used in obtaining the values given in the preceding table.

The stopping of the steady arc and consequently the end of period 4 may be due to one or the other of two causes. These are (a) the exhaustion of the energy supply which results in the gradual reduction of the current to zero and the cessation of the arc, as is shown in figures 11 and 14, or (b) the closing of the primary breaker which has the effect of quickly extinguishing the spark, as is shown at *a* in figure 13. In the former case there is at very small currents a rather rapid increase of the sustaining voltage (as at *a*, figure 16) to a value which at the instant of cessation of the spark may be double its normal value. The secondary current consequently drops to zero at a somewhat more rapid rate than during the major portion of period 4. The "natural" or uninterrupted dying out of the spark usually occurs in magnetos operating at moderate speeds and with reasonably long spark gaps, and almost invariably occurs in battery systems. It may be considered as the normal mode of operation of the system.

Owing to the large number of variables (such as current at break, rotational energy, and extinction of the spark by the closing breaker) which affect the total heat liberated in the gap, it is impracticable to accurately predetermine the heat per spark for any particular condition. Plot 25 shows how this heat (observed calorimetrically) varies with magneto speed for a particular German Bosch ZH6 magneto.

PERIOD 5.

If the magneto is operating at very high speed or on a very short spark gap, the primary contact breaker may close before the spark has died out. In this case the circuit conditions are again changed and an additional transition period 5 must be considered. The sequence of events during this period is quite closely the inverse of that occurring during period 3. The decreasing flux caused by the decreasing secondary current induces an E. M. F. in the primary turns which rapidly builds up current in the now short-circuited primary winding. This increase of current in turn, by its mutual induction on the secondary turns, rapidly decreases the secondary current. The net effect is that the remaining ampere turns linking the main flux are transferred from the secondary back to the primary and the spark is extinguished. At the same time the primary condenser which had been charged to the small voltage given by the quotient of E_s divided by the ratio of turns, discharges through the contact, and later the secondary capacity is similarly discharged. The entire duration of the period is extremely short and is of the order of 0.00005 second.

PERIOD 6.

Period 6 may be defined as lasting from the end of period 5 until the armature has rotated to the position where it receives maximum flux from the magnets. During this time the primary current continues to decay approximately according to the exponential law

$$I = I_0 e^{-\frac{R}{L}t}$$

where R and L are the resistance and inductance of the primary circuit and I_0 is the current at the end of period 5. The value of $\frac{R}{L}$ for this circuit is much smaller than for the circuit formed of the secondary winding and spark, so that the rate of decrease of current is quite slow, and an appreciable current may be flowing, when the position of maximum flux is reached, and period 1 of the next alternation begins.

In some cases this interference may be so great as to cause the succeeding spark to miss fire as shown in figure 17. In cases where the spark dies out before the closing of the breaker, period 6 follows immediately after period 4 and the circuit is practically free from current throughout the period.

During the interval after the dying out of the spark and before the closing of the breaker there may remain a small amount of local eddy currents in the iron core and pole pieces. As these decay exponentially they induce in the winding an appreciable E. M. F. such as is shown at *b* in figure 16. After the closing of the breaker, this E. M. F. reestablishes a small primary current in the original direction, as shown at *a* in figure 12. These minor effects afford possible but rather inaccurate means of estimating the magnitude of the eddy currents and hence their much more serious effect during period 2.

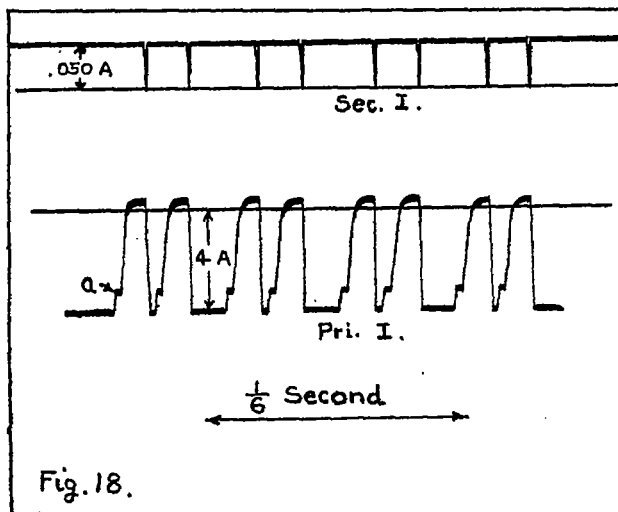


Fig. 18.

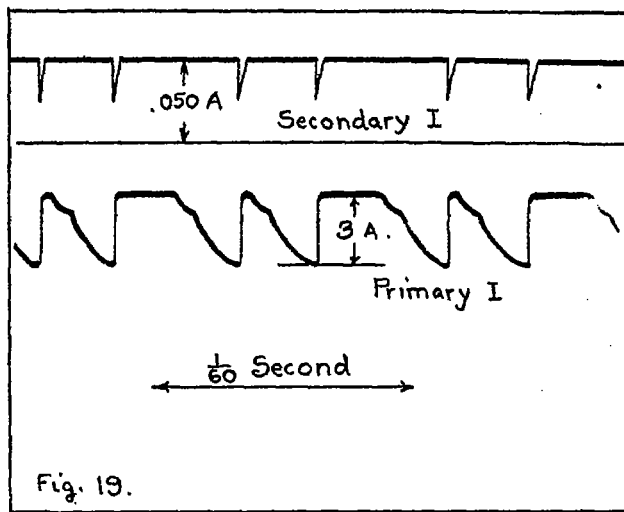


Fig. 19.

BATTERY SYSTEMS.

In the case of the usual arrangements of battery systems, the typical connections of which are shown in figure 2, period 1 may be defined as lasting from the closing of the primary contact to its opening, and is quite closely analogous to period 1 for a magneto. The primary current builds up during this period approximately according to the equation

$$I = \frac{E}{R_p} \left(1 - e^{-\frac{R_p}{L_p} t} \right)$$

but may depart somewhat from this because of the varying permeability of the iron core and the heating and consequent change in resistance of part of the circuit. This rise of current is shown in figures 18 and 19. In the so-called "closed circuit" type of system, period 1 lasts during a constant angular motion of the engine shaft and its duration is consequently shorter the higher the speed. In the "open circuit" systems the circuit is closed for a constant time interval at all speeds and this interval is usually much less than required for the current to approach the constant value $\frac{E}{R}$.

The energy which can be stored in the magnetic field during this period is usually decidedly less than that obtained with a magneto at normal speed because of the lower voltage available. The battery system usually operates on 6 or 12 volts, while a magneto may give a primary peak voltage from 50 to 100 volts at high speed. The battery, however, maintains its voltage at all speeds while the magneto may give only 4 or 5 volts peak at 100 revolutions per minute.

Periods 2, 3, and 4 are practically the same in both battery and magneto systems except that the effect of the rotational energy is absent in the battery system, and the spark heat for the same inductive energy is correspondingly reduced. Owing to this small energy content, the spark almost invariably dies out before the closing of the contact for the next spark, as shown in figures 18 and 19. Consequently, period 5 is absent and the circuit is entirely dead during period 6.

CONCLUSIONS.

It appears from the above analysis that periods 1, 4, and 6 are of comparatively long duration and the phenomena occurring therein are relatively slow and well understood. Periods 2 and 3, on the other hand, are extremely short, and very little experimental data are available to confirm or disprove the theoretical speculations as to what takes place. These two periods are, however, in a sense the most important of the entire cycle since it is the rise of voltage in period 2 which determines whether or not a spark passes at all, and the actual ignition of the mixture probably occurs during period 3. The usual forms of oscillograph are entirely unable

to analyze processes of such short duration, but the Braun tube (or cathode ray oscillograph) seems to afford a promising tool for studying these phenomena.

It seems evident that the distributed capacity of the secondary winding and high tension leads is of great moment in determining the maximum voltage attained in period 2. Also the eddy currents cause a very serious drain of energy, particularly in magnetos with solid pole pieces, though their effect is probably quite small in battery systems in which the magnetic circuit can be thoroughly laminated. Convenient methods of measuring these two effects are greatly needed. Preliminary measurements of the apparent resistance and inductance of the windings with an alternating current bridge at frequencies up to 3,000 cycles throw some light on this problem, and if a convenient way of interpreting the results can be worked out, this method may prove useful.

The requirements of an ignition system are quite different from almost any other form of electric generating system and are in some respects conflicting in character. A high voltage is required to jump the spark gap through the compressed gas in the engine cylinder. While this is usually only 5,000 to 6,000 volts, it may be very materially increased by oil films on the electrodes and a cold and consequently dense charge when starting an engine. Such a high voltage, of course, requires a large number of secondary turns. On the other hand, the spark plugs frequently become coated with a conducting film of carbon, which drains the energy during period 2 in much the same manner as the eddy currents. It then becomes necessary to supply such a large current that the IR drop in the carbon deposit is equal to the sparking voltage of the gap in order to produce a spark. Since the secondary current during periods 3 and 4 is limited to the value which produces the same ampere turns around the armature core as did the primary current before "break," this second condition requires a small number of secondary turns.

Recent measurements at the British National Physical Laboratory indicate that the actual energy required for ignition is very small compared to that furnished by any commercial form of ignition system, and any excessive amount of power is slightly detrimental in that it increases burning of the spark plug and contact breaker terminals. The paradoxical requirement is therefore for a system furnishing large current and voltage but small power.

A possible solution to this problem lies in the use of a suitable subsidiary spark gap and condenser as used in the Lodge arrangement and similar high frequency systems, in which the voltage is made as great as possible and the large current required by a fouled plug is obtained by the sudden discharge of a condenser through the auxiliary gap. The presence of the condenser, however, tends to reduce the maximum voltage attainable and to some extent defeats its own purpose. Report No. 57 gives the results of preliminary work on this type of device.

REPORT No. 58.

PART II.

TRANSFORMATION RATIO AND COUPLING IN HIGH TENSION MAGNETOS.¹

By F. B. SILSBEE.

RÉSUMÉ.

This report describes a convenient method for measuring the ratio of turns of high tension magnetos or induction coils. Two resistances are connected between the high tension terminals and ground, and a galvanometer is connected between the junction of the resistances and the junction of the primary and secondary windings. The resistances are then adjusted until no kick of the galvanometer occurs when the magnetic flux through the coils is suddenly varied. This variation in flux may be made by moving the rotor of the magneto or by interrupting a current in either winding. From measurements by both methods an estimate of the magnetic leakage and coupling coefficient is obtained. Results obtained on various magnetos by this method are given. The ratios are usually between 40:1 and 70:1, and the magnetic leakage flux is only 2 to 4 per cent of the flux common to both windings.

INTRODUCTION.

A knowledge of the ratio of turns or more strictly the ratio of magnetic linkages between the primary and secondary windings of magnetos or spark coils is frequently needed, both in predicting the performance to be expected from a given coil and in analyzing the results of oscillographic tests, etc. The method which is described in this report is similar to the alternating current methods used in obtaining the ratio of transformers and no claim is made for novelty in respect to it. It has, however, been found very useful in connection with the investigation of ignition problems and is capable of all the accuracy needed in such work.

PROCEDURE.

For simply obtaining an approximate value for the ratio of turns the connections shown in figure 1, are used. Here S and P are the secondary and primary windings of the magneto or induction coil, respectively. R_1 and R_2 are noninductive resistances, one of which should be adjustable. G is preferably a ballistic galvanometer of fairly long period, but almost any type of galvanometer can be used. In obtaining the results which are given in the later sections of this report a small Paul unipivot galvanometer of about seven ohms resistance was used. In case only moderate accuracy is needed, any low range direct current milliammeter or millivoltmeter is suitable. With the connections as shown the magnetic flux through the windings is suddenly varied, as by rotating the armature 180 electrical degrees, and the resulting throw of the galvanometer noted. The resistance R_1 (or R_2) is then varied until this throw is reduced to zero. When this condition is attained the ratio of flux turns is given by the formula

$$n_m = \frac{N_s \Delta \phi_s}{N_p \Delta \phi_p} = \frac{S + R_1}{P + R_2} = \frac{N_s}{N_p}, \text{ approx.} \quad (1)$$

Here N_s and N_p are the primary and secondary turns, respectively, and $\Delta \phi_s$ and $\Delta \phi_p$ are the respective changes in the flux linking the two coils, and are of course nearly equal in value. S , P , R_1 and R_2 are the values of the corresponding resistances. Care must be taken that the

¹ This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 15.

resistances of the circuit remain constant when the flux is varied, and to secure this condition the carbon brushes which are usually used in magnetos must be replaced with metal brushes or flexible wire connections.

MATHEMATICAL THEORY OF METHOD.

The E. M. F. induced in the primary by the changing flux is

$$E_p = -N_p \frac{d\varphi_p}{dt} \quad (2)$$

and the secondary E. M. F. is similarly

$$E_s = -N_s \frac{d\varphi_s}{dt} \quad (3)$$

Applying Kirchhoff's laws to the two circuits shown in figure 1_a we obtain the equation

$$-N_s \frac{d\varphi_s}{dt} + i_s(S + R_1) + (i_s - i_p)R_g = 0 \quad (4)$$

$$-N_p \frac{d\varphi_p}{dt} + i_p(P + R_2) + (i_p - i_s)R_g = 0 \quad (5)$$

where R_g is the resistance of the galvanometer and i_p and i_s are the instantaneous currents in the two circuits.

Integrating these with respect to time from t_1 to t_2 gives

$$-N_s \Delta\varphi_s + (S + R_1) \int_{t_1}^{t_2} i_s dt + \int_{t_1}^{t_2} R_g (i_s - i_p) dt = 0 \quad (6)$$

$$-N_p \Delta\varphi_p + (P + R_2) \int_{t_1}^{t_2} i_p dt - \int_{t_1}^{t_2} R_g (i_s - i_p) dt = 0 \quad (7)$$

where $\Delta\varphi_s$ and $\Delta\varphi_p$ are the changes in flux between the initial and final conditions. Since R_g is constant, it can be taken outside of the integral and the third term in each equation becomes

$$R_g \int_{t_1}^{t_2} (i_s - i_p) dt = R_g \int_{t_1}^{t_2} i_g dt \quad (8)$$

Now, if the time interval during which the change occurs is short compared with the natural period of the galvanometer, the deflection will be proportional to $\int i_g dt$, and since the resistances were adjusted to give zero deflection we have

$$\int_{t_1}^{t_2} i_g dt = 0, \text{ or } \int_{t_1}^{t_2} i_s dt = \int_{t_1}^{t_2} i_p dt. \quad (9)$$

Dividing equation (6) by equation (7) gives

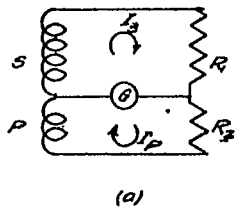
$$\frac{N_s \Delta\varphi_s}{N_p \Delta\varphi_p} = \frac{(S + R_1) \int_{t_1}^{t_2} i_s dt}{(P + R_2) \int_{t_1}^{t_2} i_p dt} \quad (10)$$

or by equation (9)

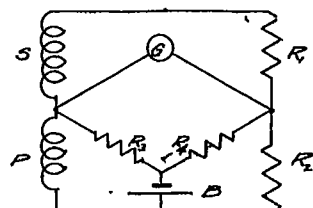
$$\frac{N_s \Delta\varphi_s}{N_p \Delta\varphi_p} = \frac{S + R_1}{P + R_2} \quad (11)$$

MEASUREMENTS WITH CURRENT IN COILS.

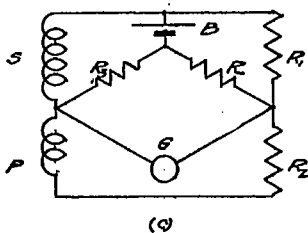
The validity of the method as just described does not depend upon the manner in which the change of flux $\Delta\varphi$ is produced, and this can, if desired, be obtained by passing a current through one of the coils and interrupting or changing the value of this current. In this case, however, while the current is flowing there will be an IR drop due to the resistance of the coil which will tend to cause a permanent deflection of the galvanometer and will thus interfere with the measurements. This can be eliminated by using a Wheatstone bridge arrangement, as



(a)



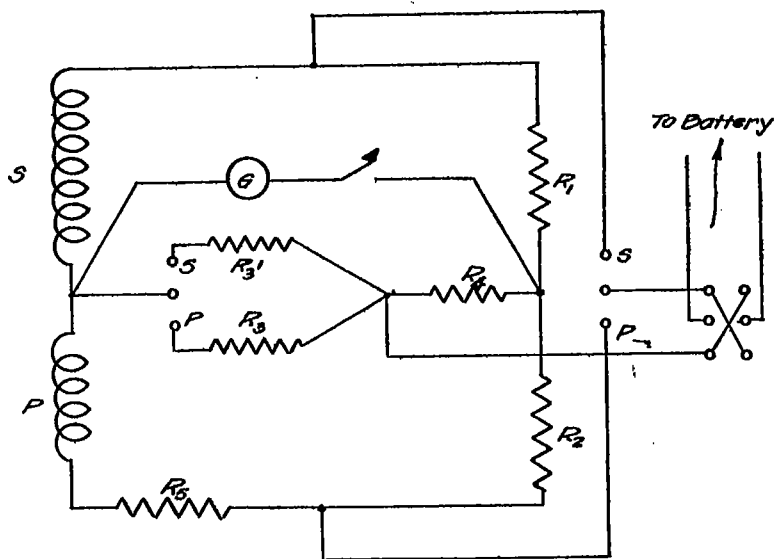
(b)



(c)

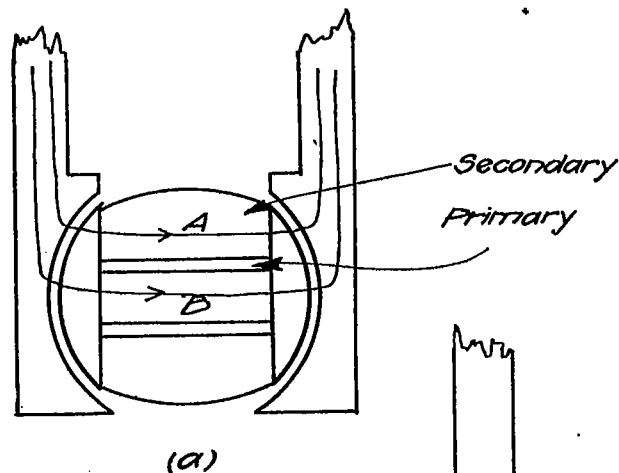
SCHEMATIC DIAGRAM OF RATIO TEST

Fig. 1.

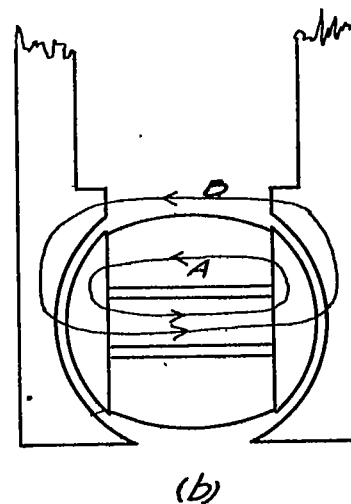


CONNECTIONS FOR RATIO TEST

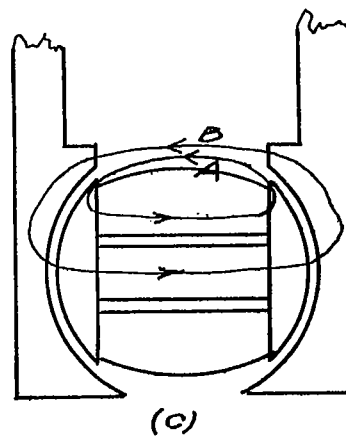
Fig. 2.



(a)



(b)



(c)

LEAKAGE FLUX IN MAGNETO

Fig. 3.

shown in figure 1_b. Here R_3 and R_4 are auxiliary resistances which, together with P and R_2 , form a Wheatstone bridge. The procedure is to first adjust R_4 so that this bridge is balanced while a steady current is flowing through the primary. The resistance R_1 is then adjusted until the galvanometer gives no throw when this current is interrupted. When a balance has been obtained under both conditions, it can be shown by reasoning similar to that in Section III that

$$n_p = \frac{N_s \Delta \varphi_s}{N_p \Delta \varphi_p} = \frac{S + R_1}{P + R_2}.$$

A similar arrangement can, of course, be used to send current through the secondary windings, as is shown in figure 1_c. Since the value of the resistances S and P are involved in the final formula, these bridge circuits serve very conveniently, if the values of R_3 and R_4 are known, to measure the resistances of the windings.

Owing to the fact that the windings are of copper, which rises in temperature considerably when carrying the working current, it is usually convenient to insert a manganin resistance of about one ohm in series with the primary winding. This serves to reduce the temperature coefficient of the circuit and greatly reduces the drift of the galvanometer due to the heating.

In the simple arrangement shown in figure 1_a, the presence of a condenser shunted around the primary has no effect upon the measurements since it is uncharged both at the beginning and end of the operation. When sending current through the windings from a battery, however, the condenser is charged initially to a voltage equal to the IR drop in the winding, and this energy adds to the ballistic throw when the circuit is broken. In actual practice, however, this effect is entirely negligible. Figure 2 shows the circuits as actually used at the Bureau of Standards in which the double throw switches marked $S-P$ serve to connect the auxiliary bridge arms for use in sending current through the secondary or primary coil, respectively, and the simple arrangement in figure 1_a is obtained when all the switches are opened. The values of resistances used are given in the following table:

- R_1 = dial box, 1000's to 10's.
- R_2 = 100 ohms fixed.
- R_3 = 5 ohms fixed.
- R_3' = 1000 ohms fixed.
- R_4 = dial box, 1000's to 1's.
- R_5 = 1 ohm fixed.

This circuit is supplied from 8 volts when using the primary winding and 80 volts when using the secondary.

DISCUSSION OF MAGNETIC CIRCUIT.

It will be observed that this method gives, strictly speaking, the ratio of flux turns in the two coils and not the ratio of turns themselves and a consideration of the magnetic circuit, as indicated in figure 3, shows the values of this ratio to be expected in the various cases. For the circuits shown in figure 1_a, in which only the field of the permanent magnet is used, it is evident from figure 3_a that some of the flux will pass through the secondary coil without linking the primary. The ratio n_m thus observed will therefore be greater than $\frac{N_s}{N_p}$. If the measurement is made by sending current through the primary, then, as shown in figure 3_b, all of the primary flux will not link the secondary, and the observed ratio n_p will be less than $\frac{N_s}{N_p}$. On the other hand, if the measurement is made with current through the secondary, then some of the secondary flux will not link the primary, and the observed ratio n_s will be greater than $\frac{N_s}{N_p}$. In either of the last two cases, the departure from the ratio of turns will be greater when the magnetomotive force of the coil aids that due to the permanent magnets than when it opposes it, as the iron is then more nearly saturated and less permeable. Typical results on a magneto of the shuttle core type which shows these variations in apparent ratio is given in Table I.

TABLE I.—Observed flux-turn ratios in Berling S-18, magneto shuttle core type.

Position of armature axis.	Ratio measured by—		
	Current in primary n_p	Magnet flux n_m	Current in secondary n_s
Parallel to flux aiding magnets.....	55.6	59.4
Perpendicular to magnet flux.....	56.4	57.1	57.4
Parallel to flux opposing magnets.....	55.9	57.8
Mean.....	56.0	57.1	57.9

$$\sqrt{\frac{L_2}{L_1}} = 56.9 \quad K = \sqrt{\frac{M^2}{L_1 L_2}} = .984.$$

If the windings are regarded as independent coils having inductances L_1 and L_2 , and a mutual inductance M , then we may write

$$n_p = \frac{M}{L_1} \text{ and } n_s = \frac{L_2}{M}$$

The coefficient of coupling k , defined as $\sqrt{\frac{M^2}{L_1 L_2}}$, is therefore given by $\sqrt{\frac{n_p}{n_s}}$. The ratio of the inductances is similarly given by $n_p n_s$.

As will be seen by reference to the data given in Table II, the value of k is very nearly unity, which means that the energy is very easily transferred from primary to the secondary circuit at the instant of break. The effect of the few per cent by which k departs from unity upon the operation of the magneto is very complex, but the energy involved in the leakage flux is obviously small compared with the total amount of energy stored.

RESULTS ON VARIOUS MAGNETOS.

The following table gives the result of measurements made by the method outlined above on a number of magneto and ignition coil systems. The values of the observed ratio with all three connections are given, also the coefficient of coupling and the square root of the ratio of secondary to primary inductance. This latter figure is probably the best estimate available of the true ratio of turns for each winding.

TABLE II.

Magneto.	n_m	n_p	n_s	$\sqrt{\frac{L_2}{L_1}}$	k
American Bosch.....	48.9	47.4	49.7	48.6	0.977
Berkshire L. H.....	44.2	42.9	45.8	44.4	.968
Berkshire R. H.....	57.2	55.5	59.1	57.3	.970
B. T. H. No. 53769.....	67.8	65.8	67.8	66.6	.982
S. E. V. No. 2.....	68.3	66.1	68.4	67.2	.983
Berling D. 81.....	57.8	56.1	58.3	57.2	.980
Berling S. 18.....	57.1	56.0	58.2	57.1	.980
Lencke.....	38.5	35.6	36.7	36.2	.985
Dixie 800.....	57.0	56.2	58.4	57.3	.980
German Bosch.....	48.8	42.6	44.1	48.4	.983
Dixie 88.....	53.0	52.2	54.1	53.2	.983
Delco (Liberty).....	88.6	93.0	90.8	.953